CG

METEOROLOGICAL OFFICE
131014
12 DEC 1979
C
LIBRARY

RESTRICTED CIRCULATION

This is not an official document: it is for information only and must not be quoted in any printed publication.

Agricultural Memorandum No 863

The deposition and dispersion of spray droplets

by N Thompson

1. Introduction A great deal of information has accumulated on the dispersion by atmospheric turbulence of small, and essentially neutrally buoyant, particles released near the surface and which are not captured in any significant numbers by deposition onto the underlying surface (eg. Pasquill 1974). This situation applies to non-sticky particles with diameters up to a few microns, travelling over dry vegetation. The fallspeeds (v_s) of these and larger particles are given in Table 1.

Table 1 Terminal velocities of drops of unit density (after Chamberlain 1975)

Drop diameter (microns)	Terminal velocity (ms^{-1})
1	3×10^{-5}
5	8×10^{-4}
10	3×10^{-3}
20	1×10^{-2}
30	3
50	7
100	25
150	50
200	75
250	95×10^{-2}

Wind and sunshine produce turbulent up and downdraughts and these, combined with horizontal movement, increase the effective settling velocity of the particles near the surface to v_d (the "deposition velocity"). v_d for large particles ($\gtrsim 100\mu$) will be close to v_s, but where the size is a few microns v_d may be at least an order of magnitude larger than v_s when stronger winds increase the impaction efficiency (Chamberlain 1975).

The magnitude of the deposition velocity depends partly on whether or not the particles bounce off the underlying vegetation to become resuspended in the airflow above the crop. This complication does not exist for droplets because these behave as if "sticky" and will be retained on impact if less than about 50 μ diameter. Larger droplets may shatter on impact but thereafter most of their volume is likely to be retained below the top of the crop canopy.

2. Droplet size distributions produced by sprayers Conventional sprayers produce a very broad size spectrum with a volume mean diameter around 250 μ, but with most of the droplets below 50 μ diameter. Controlled droplet (CD) devices produce

FH2B

most of the drops in a much narrower size range if properly designed and maintained: a typical VMD might be 250 μ , with the majority of droplets greater than 150 μ . Ultra-low volume (ULV) systems such as the ULVAMAST also create a spectrum of droplets much narrower than those from conventional sprayers and shifted to much smaller sizes. For example an ULVAMAST set to produce a VMD of 100 μ will produce the majority of its droplets with diameters greater than 80 μ . Spectra from three commercial sprayers obtained by Bals (1978) are given in Figure 1.

3. Droplet deposition and diffusion The main drops from efficient high-volume CD sprayers have fall speeds of around 1 ms^{-1} (Table 1), comparable to vertical turbulent velocities in the atmosphere, and will settle onto foliage without a serious drift hazard unless either (a) the wind is strong enough to interfere seriously with the production of the drops, broadening the spectrum so that droplets with sizes significantly less than those expected occur or (b) the wind is strong enough that turbulent velocities larger than $\sim$ 1 ms^{-1} (the settling velocity) occur: this latter requires winds in excess of a few metres per second. Drift of droplets smaller than the target size of 200 - 300 μ will be discussed later. Droplets from ULV devices which are usually set to produce chiefly $\sim$ 80 μ size have fall speeds mainly in the range 0.05 - 0.25 ms^{-1}. Here there will be some drift of not only the small numbers of very small droplets which are produced, but also of the main size ($\sim$ 80 μ): indeed this type of device relies on drift to produce a satisfactory deposit pattern on the sprayed crop.

Results such as those given in Figure 1 may be used in the estimation of deposit densities produced by sprayers at different distances downwind from the release point. Table 2 gives the relative numbers and volumes of droplets emitted by four types of sprayers on the assumption that the emission rate for the ULV sprays is 4% of both of the other two. The Table also includes the volume of active chemical in each size range, assuming a total chemical emission for the high volume sprayers twice that of the low volume devices: one of the advantages claimed for the low volume systems is that by producing many fairly small droplets of similar size it is possible to obtain a very even coverage of chemical and so permit the use of less chemical than large droplet sprayers and still achieve the same disease control - this does not appear to have been proved conclusively in field experiments but the assumption is made here that a reduction of one half may be made. It is clear from the Table that the conventional sprayer emits many times more droplets in the smaller size ranges. However what is important from the point of the drift hazard is not the droplet volume in each of the size ranges but the corresponding volumes of active chemical. On this basis the low-volume sprayers will provide much the greater hazard for droplet sizes between about 30 μ and 120 μ . Another consideration is that droplets from the conventional sprayer are likely to be water-based and so will evaporate quickly if small, whereas those from ULV devices may be oil-based and very slow to evaporate. Thus the small water-based drops will probably decrease to half their original size in a few seconds in a dry atmosphere (Figure 2): they will then have smaller terminal and deposition velocities and be somewhat more likely to diffuse harmlessly into the atmosphere.

The drift hazard from droplets of different sizes may be assessed by applying theories of deposition and atmospheric diffusion but because these are not entirely straightforward their discussion has been relegated to the Appendix to this paper and only the results from the theories will be described here. It must be stressed that there is no entirely satisfactory but still fairly simple theory of the deposition/diffusion process and any results presented here will be approximations, although probably adequate for the present discussion.

Deposit densities of droplets sprayed in very light winds are likely to be very variable in the case of small droplets because wind direction fluctuations are large in these conditions: the airflow may even reverse at times. For these reasons a satisfactory lower wind speed for effective ULV spraying is unlikely to

be much less than 2 ms^{-1} in sunny conditions with high thermal instability. Light winds will favour however very even spraying if large droplets are produced. What is more important to establish is the upper wind speed limit. The range of droplet fallspeeds to be considered is from a few centimetres per sec up to at least 1 ms^{-1}. Reference to the Appendix and in particular to equations A.19 and A.20 shows that deposit densities at different distances downwind are functions of the height of emission of the droplets (Z), a diffusion parameter (a) whose value increases with increasing instability, and the ratio (f) of settling velocity and mean speed of travel of the particles downwind. Figure 3 shows plots of deposit density (in units per square metre) against distance downwind from a crosswind line release of strength 1 unit per metre. Results are given for two release heights (0.5 and 2.0 m), two values of a corresponding to rather unstable and neutral stability conditions and a range of f - values between 0.005 and 0.5.

Inspection of the Figure shows that for either release height drift will be negligible in unstable conditions only when f is very large ($\gtrsim 0.5$). Significant drift occurs for f -value as large as 0.2, and the near-coincidence of the curves as f decreases below 0.02 demonstrates that droplets behave in these cases in a fashion nearly independent of settling. What constitutes unacceptable drift in these stability conditions has to be determined by reference to spraying rate, plant vulnerability and chemical toxicity. Spraying in near-neutral conditions leads to a generally larger drift hazard: meteorological conditions tend towards neutrality as wind speed increases and most cases with winds greater than about 6 ms^{-1} will be near-neutral (or only slightly unstable if insolation is very large). The Figure shows once again that $f \gtrsim 0.5$ is an approximate rule for negligible drift in these conditions.

The curves in the Figure may be used to determine deposit densities at any distance downwind of a sprayed area. If the place of interest is well downwind of the sprayed field then the total deposit there may be quickly obtained by summing contributions to the deposit from spray released over broad adjacent crosswind strips of the field. For example if the point is 100 m downwind of the area sprayed, the strips are assumed to be 10 m wide and the spray density is X units per 10 m^2, then the deposits for the appropriate values of f and stability are read from the graph at distances of 105, 115, 125 m etc, summed and multiplied by X to obtain the desired results. If the spraying is approximated using 20 m wide crosswind strips, then the deposit is the sum of the values at distances 110, 130, 150 m etc, multiplied by $2X$ (and so on). If the spray is not monodisperse the same procedure is adopted for suitably narrow size ranges of droplets, each with its own f -value, source strength and deposit pattern. The required final answer is then obtained by summing the separate contribution to the deposit from each size range.

Any comments or suggestions on this paper should be referred to the author.

Meteorological Office, Met O 8a
London Road
Bracknell, Berkshire

November 1979

References

Bache, D H and Sayer W D 1975 Transport of aerial spray,
I. A model of aerial dispersion, Agricultural Meteorology, 15, 257-271

Bals, E J 1978 The reasons for CDA (controlled droplet application), Proceedings 1978 British Crop Protection Conf., Weeds, 659-666

Chamberlain, A C 1967 Transport of Lycopodium spores and other small particles to rough surfaces, Proc. R Soc. A., 296, 45-70

Chamberlain, A C 1975 The movement of particles in plant communities, Chapter 5, Vegetation and the Atmosphere Vol I (Ed. Monteith, J), Academic Press, London

Csanady, G T 1973 Turbulent Diffusion in the Environment, D Reidel Company, Dordrecht

Pasquill, F 1974 Atmospheric Diffusion, Ellis Horwood, Chichester

Table 2 Number of droplets ($x10^6$) and volumes emitted per ha in different size ranges by four different sprayers (after Bals 1978)

Mean of size range (μ)	Number of droplets				Total volume (in arbitrary units)				Volume of active chemical (in arbitrary units)			
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
412	0	0	1150	1470	0	0	8.0M	10M	0	0	161K	206K
211	0	0	10100	6660	0	0	9.5M	6.3M	0	0	190K	125K
137	0	923	4960	6260	0	237K	1.3M	1.6M	0	59K	25K	32K
99	1690	4193	2440	5530	164K	407K	237K	540K	41K	102K	4.7K	11K
74	10450	2479	1390	5150	423K	100K	56K	209K	106K	25K	1.1K	4.2K
57	7210	1043	840	4870	134K	19K	16K	90K	33K	4.8K	310	1.8K
45	3220	463	560	5050	29K	4.2K	5.1K	46K	7.3K	505	100	920
35	1205	189	350	4840	5.2K	810	1.5K	21K	1.2K	200	30	415
27	460	80	220	4790	905	157	433	9.4K	226	40	9	190
21	180	35	145	4800	167	32	134	4.4K	43	8	3	90
17	70	14	100	4750	34	7	49	2.3K	9	2	1	47
13	25	7	85	4770	5	1	19	1.0K	1	0	0	21
10	12	4	0	4440	1	0	0	444	0	0	0	9
8	0	0	0	4730	0	0	0	242	0	0	0	5
6	0	0	0	4460	0	0	0	96	0	0	0	2

(a)	"Battleship"	VMD 75m	4 l/ha total	1l/ha active chemical
(b)	"Ulvamast"	104m	4	1
(c)	"Battleship	250m	100	2
(d)	Conventional (Fanjet)	273	100	2

Figure 1 Droplet size spectra from conventional and CD sprayers (after Bals (1978))

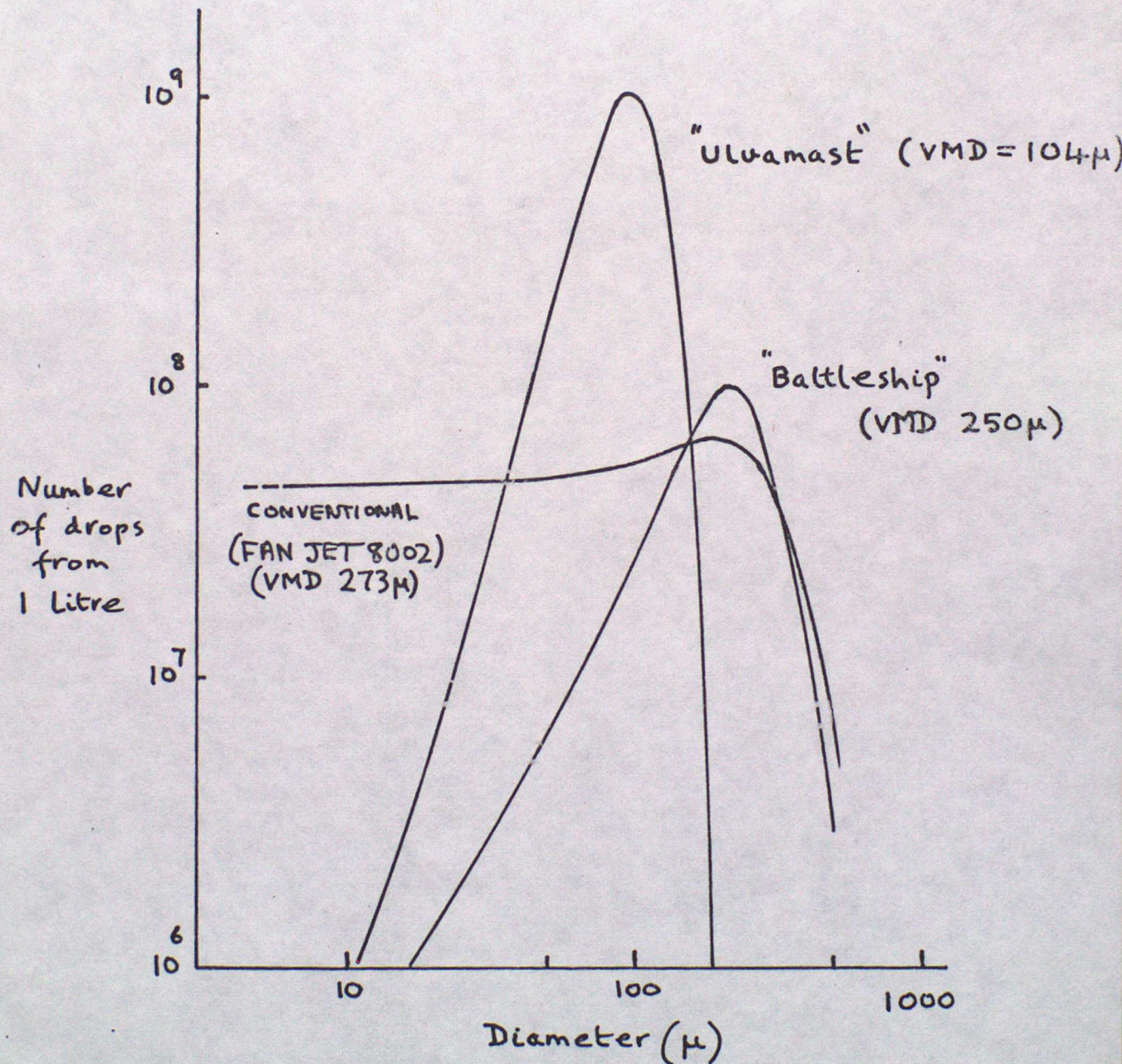


Figure 2. Fallspeed, and time for pure water droplets to decrease to half their initial diameter in air with relative humidity of 60%

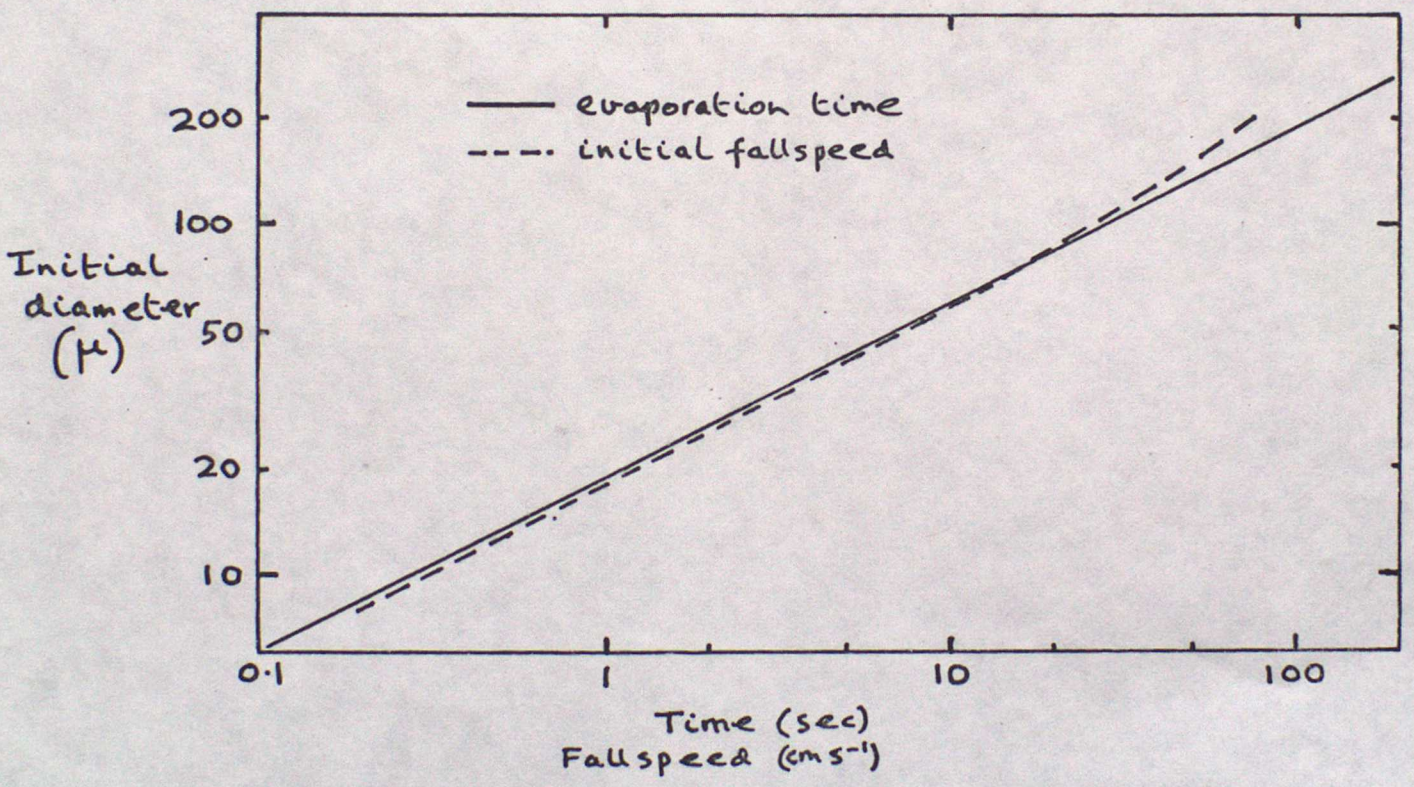


Figure 3 Deposit densities at different distances downwind

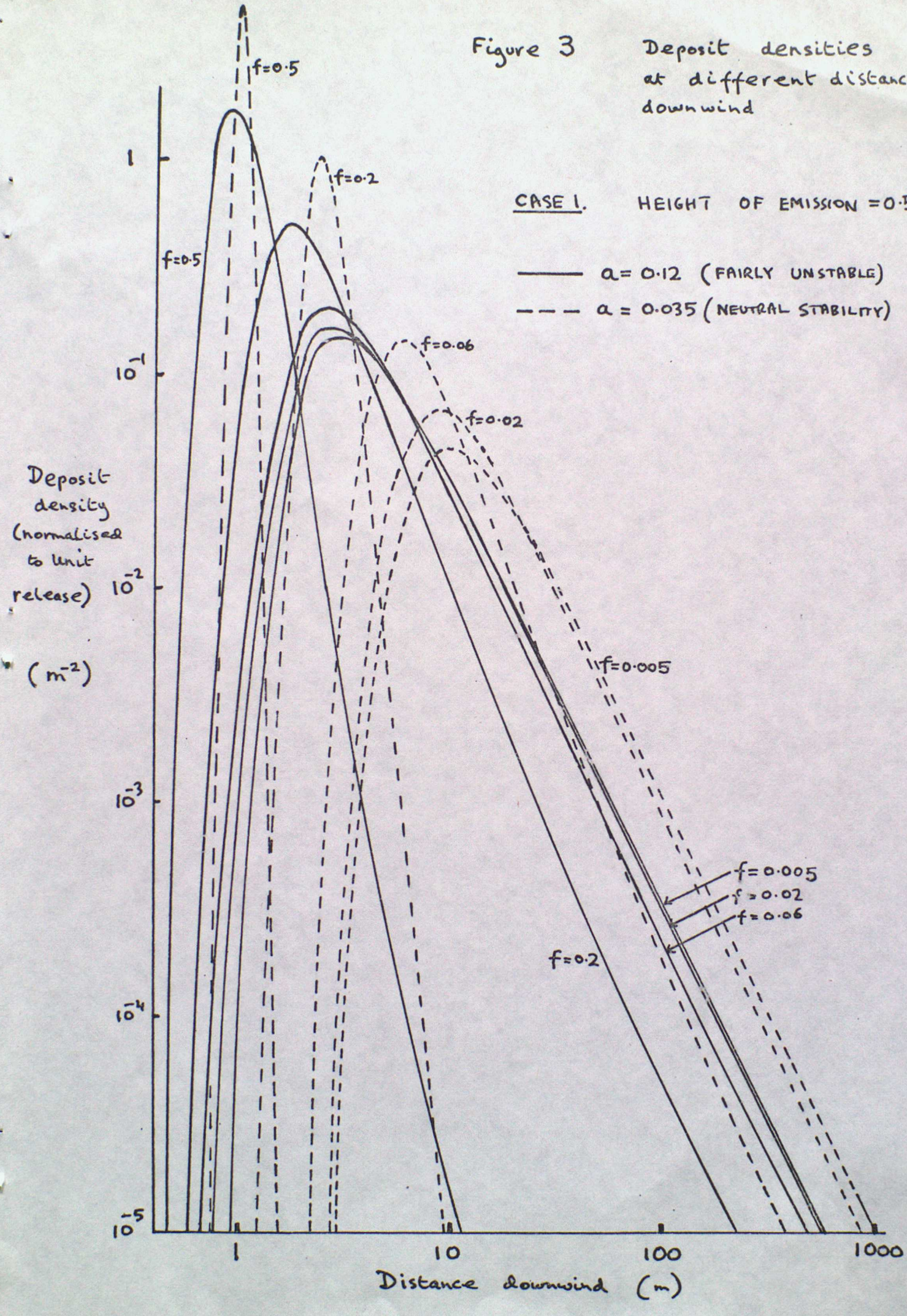
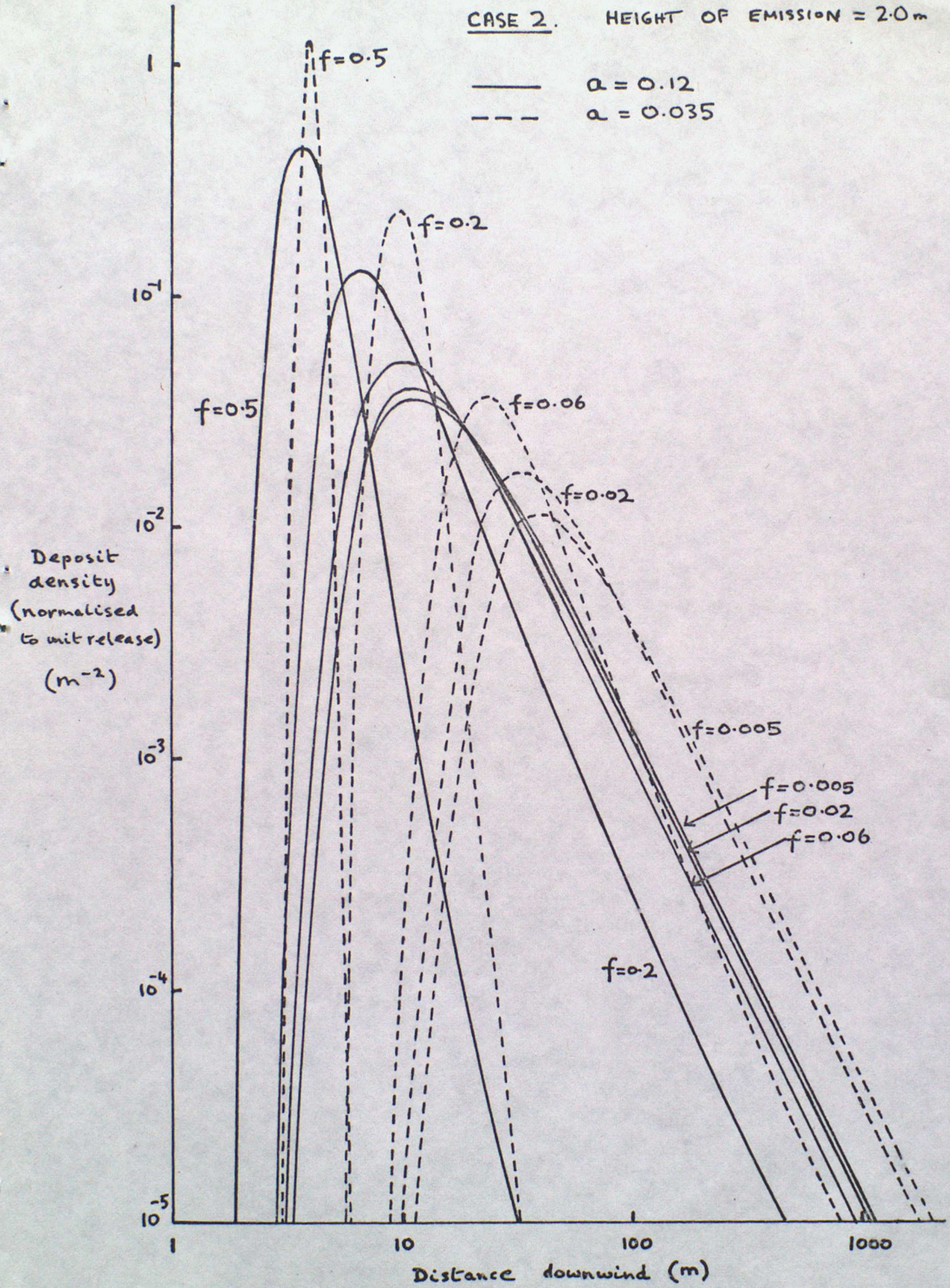


Figure 3 (CONTD.)



Appendix Theoretical treatments of deposition and diffusion

A1. Large drops These (say 300–500 microns diameter) have terminal velocities between about 2 and 4 ms^{-1} and their deposition pattern on a crop may be determined purely ballistically because the effects of vertical atmospheric turbulence on their distribution will be small usually. Thus the distance of maximum deposition for monodisperse droplets released at a height Z above a crop is given by

$$x_m = Z\bar{u}/v_s \qquad (A.1)$$

where $\bar{u}$ is the wind speed averaged between height of release and top of crop. For conditions close to neutral stability one may integrate the logarithmic wind profile to obtain

$$\bar{u} = \frac{u_*}{kZ}\int_h^{Z+h} \ln\left(\frac{z-d}{z_o}\right) dz$$

$$= \frac{u_*}{kZ}\left((Z+h-d)\ln\left(\frac{Z+h-d}{z_o}\right) - (h-d)\ln\left(\frac{h-d}{z_o}\right) - Z\right) \qquad (A.2)$$

where

$$\frac{u_*}{k} = U_{10} / \ln\left(\frac{10-d}{z_o}\right)$$

U_{10} = 10 m wind speed
h = crop height
z_o = crop roughness length ($\sim 0.1h$)
d = crop zero plane displacement ($\sim 0.6h$)

For example, in the case of a crop of height 1m with drops released 1 m above the foliage top, then $\bar{u} = 0.47\,U_{10}$. If the 10 m wind speed is 5 ms^{-1} and the drops have a fall speed of 2 ms^{-1} (drop diameter $\sim$ 300 microns) then $x_m = 1.17$ m. The standard deviation (σ_{x_m}) of x_m due to typical horizontal turbulent fluctuations of the wind about its mean is given by

$$\sigma_{x_m} \simeq x_m\,\sigma_v/\bar{u}$$

In near-neutral conditions

$$\sigma_v \simeq \sigma_{\bar{v}} \simeq 2.5\,u_* = u_*/k \qquad (A.3)$$

and so

$$\sigma_{x_m} \simeq \frac{U_{10}\,x_m}{\bar{u}} / \ln\left(\frac{10-d}{z_o}\right) = \begin{cases} 0.47x_m & (z_o = 0.1\text{m}) \\ 0.32x_m & (z_o = 0.01\text{m}) \end{cases}$$

A2. Smaller drops Chamberlain (1975) has summarized a considerable amount of work on the deposition of (mainly) particles (usually spores) to real and artificial surfaces, outdoors and in wind tunnels, but presents very few results for droplets. Foliage is essentially a perfect sink for droplets but small particles tend to bounce off dry vegetation, so decreasing their effective deposition velocity to less than that for droplets. Following Chamberlain, a simple theory of deposition of droplets may be developed by making the following assumptions:

(i) except near the surface the droplets follow eddy motions of the air, with a constant vertical velocity (the terminal velocity) superimposed

(ii) the wind profile above the surface is logarithmic (the neutral wind profile

(iii) eddy diffusivities for matter and momentum are equal and given by $K(z) = ku_*(z-d)$, appropriate to the neutral wind profile.

If the downward flux of monodisperse droplets of diameter D is $F(D)$ ($m^{-2}s^{-1}$) then the diffusional flux is $F(D) - v_s X$ where X is the droplet concentration per cubic metre. Then:

$$K(z)\frac{\partial X}{\partial z} = F - v_s X(z) \qquad (A.4)$$

or

$$ku_*(z-d)\frac{\partial X(z)}{\partial z} = F - v_s X(z) \qquad (A.5)$$

After integration

$$\frac{v_s}{ku_*}\ln(z-d) = -\ln\left(\frac{F - v_s X(z)}{B}\right) \qquad (A.6)$$

where B is a constant of integration. It is then assumed that the effective sink for impaction of droplets on the foliage is at a height $d+z_p$ so that $X(z) = 0$ when $z = d+z_p$. Equation (A.6) may then be written

$$\frac{F - v_s X(z)}{F} = \left(\frac{z_p}{z-d}\right)^{\alpha} \qquad (A.7)$$

where $\alpha = v_s/ku_*$

The definition of velocity of deposition is

$$v_g = F/X(z) \qquad (A.8)$$

and so for a reference height z_1 one may write

$$v_g(z_1) = v_s/\left(1 - (z_p/(z_1-d))^{\alpha}\right) \qquad (A.9)$$

Chamberlain (1967) presented wind tunnel results for deposition of Lycopodium spores to sticky surfaces which were consistent with the assumption $z_p \simeq z_o$ and on this basis the following table may be drawn up showing how v_g varies with droplet size, wind speed and crop height (crop roughness). It is

Table A2.1 Values for v_g for droplets of different diameters (reference height $z_1 = d+1m$)

Droplet diameter (μ)	v_s (ms^{-1})	v_g ($ms^{-1} \times 10^{-2}$)					
		$U_{10} = 2ms^{-1}$		$5ms^{-1}$		$8ms^{-1}$	
		z_o=0.01	0.1	0.01	0.1	0.01	0.1
20	1.2×10^{-2}	1.7	3.7	3.2	8.1	4.7	12.7
50	7×10^{-2}	7	7.8	7.5	11.5	8.5	15.9
75	15×10^{-2}	15	15.1	15	17.4	15.4	21.1

seen that for the smallest drops the deposition velocity is increased significantly by atmospheric turbulence, even over smooth surfaces in light winds, but the 50 and 75 micron sizes have deposition velocities little different from settling velocity unless the wind is quite strong and the underlying surface rough.

Csanady (1973) applied the standard gaussian treatment of atmospheric diffusion to the case of a cloud of droplets of strength Q released at height Z above the zero plane and with settling velocity equal to the deposition velocity:

the lower boundary (of foliage) was assumed to be completely absorbing. The concentration at height z after time t is then

$$\chi(t,z) = \frac{Q}{(2\pi)^{1/2}\sigma_z \bar{u}} \exp\left(-\frac{(2v_s t(z-d-Z) + v_s^2 t^2)}{2\sigma_z^2}\right)$$

$$\left[\exp\left(-\frac{(z-d-Z)^2}{2\sigma_z^2}\right) - \exp\left(-\frac{(z-d+Z)^2}{2\sigma_z^2}\right)\right] \qquad (A.10)$$

here σ_z is the standard deviation of the distribution of material in the vertical in the case of unbounded diffusion, without therefore any deposition. Rate of deposition per square metre is

$$I(t) = -v_s \chi\Big|_{z-d=0} - D\frac{\partial \chi}{\partial z}\Big|_{z-d=0} = -D\frac{\partial \chi}{\partial z}\Big|_{z-d=0} \qquad (A.11)$$

D is the effective diffusion coefficient defined, following the Fickian analogy, by

$$\frac{d\sigma_z^2}{dt} = 2D \qquad (A.12)$$

or $$D = \sigma_z \frac{d\sigma_z}{dt}$$

For small release height (less than a few metres) one may use data given by Pasquill (1974) to obtain σ_z for very unstable (A), moderately unstable (B), neutral (D) and stable (F) conditions, for z_o = 0.01 m

$$\left.\begin{aligned}
\sigma_z(A) &= 0.16\, x^{0.94} \\
\sigma_z(B) &= 0.12\, x^{0.89} \\
\sigma_z(D) &= 0.097\, x^{0.81} \\
\sigma_z(F) &= 0.055\, x^{0.72}
\end{aligned}\right\} \qquad (A.13)$$

Approximate values for z_o =0.1 m are obtained by multiplying those in A.13 by 1.4. In practice it is more convenient (though less accurate) if a simple linear dependence of σ on x is assumed, and by matching values given at 200 m by (A.13) one obtains

$$\left.\begin{aligned}
\sigma_z(A) &= 0.12\, x \\
\sigma_z(B) &= 0.067 x \\
\sigma_z(D) &= 0.035 x \\
\sigma_z(F) &= 0.013 x
\end{aligned}\right\} \qquad (A.14)$$

One may then write

$$D = \bar{u} a^2 x \qquad (A.15)$$

where a is the multiplying constant in (A.14).

Differentiating (A.10)

$$\left(\frac{\partial X}{\partial z}\right)_{z-d=0} = -\frac{2QZ}{(2\pi)^{1/2}\sigma_z^3}\exp\left(-\frac{(Z-v_s t)^2}{2\sigma_z^2}\right) \qquad (A.16)$$

and using the result with (A.12):

$$-D\left(\frac{\partial X}{\partial z}\right)_{z-d=0} = \frac{2QZ}{(2\pi)^{1/2}\sigma_z t}\exp\left(-\frac{(Z-v_s t)^2}{2\sigma_z^2}\right) \qquad (A.17)$$

The analysis leading to (A.17) is appropriate to reference axes moving downwind at the mean speed of travel of the particles. Transcription to a fixed frame (Bache and Sayer 1975) is performed by considering the probability $P(x)\,\delta x$ of a particle landing in the interval $x, x+\delta x$ downwind of release: this is given by

$$P(x)\delta x = A.\left(-D\left(\frac{\partial X}{\partial z}\right)_{z-d=0}\right).\frac{\delta t}{Q} \qquad (A.18)$$

A is a factor of normalisation, which is (according to Bache and Sayer)

$$A = \int_0^\infty P(x)\,dx \Big/ \int_0^\infty \left(-D\left(\frac{\partial X}{\partial z}\right)_{z-d=0}/Q\right)dx$$

$$= 1/(1+\mathrm{erf}\,(f/\sqrt{2}a)) \qquad (A.19)$$

where $f = v_s/\bar{u}$. If the source is a crosswind line of strength Q droplets per metre then the deposit (n) per square metre at distance x downwind is

$$n = Q\,P(x)$$

$$= \sqrt{\frac{2}{\pi}}\,Q\,\frac{AZ}{ax^2}\exp\left(-\frac{(Z-fx)^2}{2a^2x^2}\right) \qquad (A.20)$$

By integrating (A.20) one obtains the number of droplets (Σn) deposited between source and distance x

$$\Sigma n = AQ\,\mathrm{erfc}\left(\frac{h-fx}{\sqrt{2}ax}\right) \qquad (A.21)$$